10 Appendix I: Discussion of Forest Management Approaches

The Division has an obligation to select a resource management approach that clearly meets our principal mandate for water supply protection and, where compatible, to choose one that meets other directives as well. In designing the approach for Division properties on the Ware River watershed, the benefits and limitations of three broad approaches were considered: naturally-managed forests, even-aged management, and uneven-aged management. Each approach is summarized below in general terms. The literature review and analysis below then considers the effects of each approach on water yield and water quality, as well as broad potential effects on secondary objectives such as wildlife habitat and aesthetics.

10.1 Naturally-managed Forests

10.1.1 Description

Natural management refers to forests, or areas within forests, in which deliberate, direct human manipulation does not occur. No forest on earth is without human impact, given that human activities affect climate, the distribution of insects and diseases, and the quality of air and precipitation throughout the globe. In the context of this plan, however, natural management refers to areas in which trees are not deliberately cut or harvested, and where changes in the forest are primarily the result of natural disturbances such as catastrophic wind, snow and ice, or autogenic processes of aging and decay. Attiwill (1994) provides an excellent review of the literature on natural disturbances in forests.

10.1.1.1 Water Yields

Tree growth and naturally occurring forest disturbances (fires, wind, disease, and insects) heavily influence the water yields from naturally-managed forests. Eschner and Satterlund (1965) studied a 491 square-mile watershed in the Adirondack Mountains of New York from 1912-1962. This study is particularly relevant to an examination of the impact of naturally-managed forests upon water yields. Land use on the watershed up to 1910 included land clearings, extensive fires, and heavy forest cuttings (chiefly logging of softwoods). In the late 1800s, the state of New York began purchasing lands in the watershed for the Adirondack Forest Preserve. From 1890 to 1910 the percentage of state-owned Forest Preserve in the watershed increased from 16% to 73%. The management policies of the Forest Preserve included laws against any cutting of trees and an active program of forest fire suppression.

The average forest density (in basal area) of the watershed increased from 65 square feet per acre in 1912 to 107 square feet per acre in 1952, due to forest growth and restrictions on cutting. Average basal area decreased to 97 square feet per acre in 1963 due in part to mortality from a windstorm in 1950. There was also a large increase in the beaver population during the study period. Throughout the Adirondacks, the number of beaver increased from an estimated 10 individuals in 1895 to an estimated 20,000 individuals by 1914, due to a prohibition on trapping introduced in 1895 and the introduction of 25 Canadian beaver and 14 Yellowstone Park beaver between 1901 and 1907. In 1965, most perennial drainages in the watershed were occupied by beaver.

The combined effects of unregulated forest growth and the increased number of beaver dams reduced the annual water yield of the watershed by 7.72 area-inches, or 23%, from 1912 to 1950. Eschner and Satterlund (1965) postulated that forest growth reduced water yields through changes in evapotranspiration and snowmelt and beaver reduced yields through evaporation losses from beaver ponds. Although the net effect from beaver was a reduction in water yield, dormant season flow increased due to reduced interception and evapotranspiration following the killing of trees in flooded areas. The general effect of unregulated forest growth in lowering water yields was offset to some extent by increases in water yields resulting from the paving, straightening, and widening of seventy-five miles of roads within the watershed during the study period.

The trend of decreased water yields from 1912-1950 was reversed due to the large number of trees that were killed by a severe storm that occurred on November 25 and 26, 1950, and the continued increase in mortality during the 13 years after the storm. According to Eschner and Satterlund (1965):

> The storm of November 1950, disrupted the associated patterns of forest stand development and streamflow change, returning both to a point nearer their 1912 levels.

In a separate study, Eschner (1978) analyzed four small watersheds in the Adirondack Mountains of New York. Logging, farming, and fires up to the early 1900s heavily impacted the East Branch of the Ausable River. Of the four watersheds, only the East Branch of the Ausable River was unaffected by the windstorm of 1950. This watershed offers a good example of a 42 year, stream-gauged period of uninterrupted forest re-growth. During this period, streamflow decreased by 4.2 area inches. Eschner concluded that this decrease was due to the natural regrowth of vegetation.

10.1.1.2 Water Quality

The impact of disturbance is perhaps the key difference between a naturally-managed and actively-managed forest. In the actively-managed forest, silvicultural management is in effect a deliberate and regulated form of disturbance. In the naturally-managed forest, most disturbances are the result of unregulated natural events (e.g., wind, fire, disease, insects, or ice). While harvesting may at times concentrate on the same species affected by natural disturbances, harvesting extent is either regulated or practically restricted, while natural disturbances are not deterred by steep or wet areas. While both actively-managed and naturally-managed forests will be exposed to certain recurring natural disturbances (e.g., hurricanes), the two systems may respond to these disturbances very differently.

In recent years, even forests isolated from developed areas are being increasingly impacted by human factors (air pollution, introduced insect/disease complexes). Eschner and Mader (1975) note:

> When extensive areas of relatively stable vegetation are set aside for wilderness, man's activities are sharply restricted. However, changes in the vegetation continue, and in some cases the possibility of catastrophic change increases...Treatment of large areas of watershed as wilderness, currently advocated by several interest groups, may not be consonant with management for maximum yields or protection of areas. On land long undisturbed, use of water by vegetation may be maximized and water yield reduced, while hazards of windthrow, insect, disease, or fire damage may increase.

Hewlett and Nutter (1969), in defining pollution, mention the potential impact of natural disturbances upon water quality:

> Because natural waters already carry materials that can degrade water for certain uses, we have some difficulty specifying just what "pollution" is. Natural water quality over the centuries has evolved the stream ecosystem under conditions that we might, rather pointlessly, refer to as "natural pollution." For our purposes, however, we shall regard pollution as man-caused and think of polluted waters as those degraded below the natural level by some activity of man. In this sense, therefore, unabused forests and wildlands do not produce polluted waters, although they may at times produce water of impaired quality.

Parsons et al. (1994), in a study of the impact of gap size on extractable soil nitrate stated:

> Large-scale mortality events leading to macroscale gap formation, which involves the simultaneous death of many adjacent trees over thousands or tens of thousands of square meters, are known to increase mineralization and nitrification rates in temperate forest ecosystems.

Tamm (1991), in reviewing the role of nitrogen in terrestrial ecosystems, noted:

> Natural agents such as storms, insect defoliations, and, above all, fire may destroy the existing vegetation and stimulate both nitrogen mineralization and nitrification, leading to temporary losses of nitrate.

Corbett and Spencer (1975) report that Hurricane Agnes and the 14 inches of rain that accompanied it caused significant erosion impacts on the Baltimore municipal watershed, chiefly due to streambank cutting and channel slumping. The authors note that these types of impacts are more related to channel depth than condition of forest cover. Hurricane Hugo caused extensive damage to coastal South Carolina. The U.S.D.A. Southeast Forest Experiment Station monitored stream waters within the Frances Marion National Forest before and after the hurricane, with a gap in monitoring for several months after the hurricane, due to access problems (McKee, 1993). The forest before the storm was mature pine-hardwoods and much of it was windthrown or snapped by the storm. Preliminary results showed increased nitrogen in streams compared with levels found in regular monitoring done before the storm. Mineralization in areas of high tree mortality, with limited soil nitrogen uptake, can raise the potential for excess mobile nitrogen that may make it to streams (Gresham, 1996). These and many other effects of Hurricane Hugo are summarized by the USDA Forest Service (Haymond and Harms, 1996).

Researchers in South Carolina are also concerned about the threat of a large forest fire due to the amount of downed material, which has increased from 8 tons/acre before the storm to 100 tons/acre after the storm. After a 1.6 acre simulated hurricane "pulldown" at the Harvard Forest, Carlson (1994) reported that downed woody debris increased from 4.1 tons/hectare in a control area to 33.5 tons/hectare. He suggests that the potential threat of fire will increase in the next several years as pulled-over trees die.

Numerous studies show that impacts from forest blowdown or a combination of blowdown and forest fire can increase tributary nitrate and phosphorus exports by several times background levels (Verry 1986 and Packer 1967 as cited in Ottenheimer 1992; McColl and Grigal 1975; Wright 1976; Schindler, et al., 1980). Soil disturbance from blowdown of large numbers of trees may also result in significant erosion (Patric, et al., 1984; White, et al., 1980). Water quality changes associated with extensive windthrow and fire confirm that dissolved nutrients and in some cases, sediment, acidity, and total organic carbon can be elevated for several years (Patric 1984; Verry 1986; Schindler, et al., 1980; Wright 1976; Corbett and Spencer 1975; McColl and Grigal 1975; Dobson, et al., 1990; Dyrness 1965 and McKee 1993). For example, nitrates increased by up to nine times and phosphorus by more than three times after extensive windthrow followed the next year by a wildfire in a monitored watershed in Ontario (Schindler, et al., 1980).

Dobson, et al., (1990), reviewing data from hundreds of lakes in New York, New Hampshire and Sweden, found strong spatial and temporal associations between percentage of watersheds affected by large blowdown events and long-term lowered pH in basin lakes. They concluded that extensive blowdown alters hydrologic pathways by channeling flow through large macropores created by rotting roots so that water is less buffered by subsurface soils and bedrock. One lake adjacent to heavy blowdown that was extensively salvaged did not acidify, leading the authors to speculate that salvage may partially counter the impacts of blowdown on acidification.

The value of advance regeneration (regeneration established before overstory removal) in reducing the impacts of natural disturbances may be the critical factor distinguishing actively managed and naturally managed watersheds. After disturbance, areas that are quickly occupied with dense, fast-growing seedling/sapling growth should minimize transitional losses of nutrients, and particulate and erosion losses. Buzzell (1991) and Kyker-Snowman (1989) compared actively managed and naturally managed forests on DCR/DWSP watersheds with regard to the presence and abundance of advance regeneration. Their findings demonstrate that active management can maintain consistently higher levels and spatial distribution of regeneration and young forest growth than those produced in unmanaged areas. Arbogast (1957) notes that a key consideration for implementing uneven-aged silviculture on previously unmanaged and undisturbed stands is to enhance age-class balance by encouraging otherwise unpredictable development of sapling and pole-sized trees.

The impact of actively managed and naturally managed forests adjacent to stream channels is discussed thoroughly in Maser et al. (1988). Although this study is focused on forests of the Pacific Northwest, some principles are applicable to the northeast. The authors documented that streams flowing through young forests and those recently harvested contain only 5-20% of the large woody material found in streams flowing through naturally managed forests. The stability and length of wood pieces is also increased in naturally managed forests. While the authors document a clear difference in the fish habitat of the two streams, they also note that the increased debris in streams bounded by naturally managed forests may impact the stability of streams.

While it may seem that large amounts of woody debris would increase the amount of decomposed organic material in streams, wood in direct contact with water decomposes very slowly. Maser et al. (1988) note that only 5-10% of a stream's nitrogen supply is derived from rotting instream debris. On the positive side, debris serves to create hundreds of dams that slow the flow of particulate material down the stream. The authors speculate that stream stabilization after floods is accelerated by large woody debris, noting that “large stable tree stems lying along contours reduce erosion by forming a barrier to downhill soil movement.”

While the forest conditions in the Pacific Northwest are very different from those in the northeast (for example soils in the northwest are less stable, forest types are different, and even-aged management using clear-cutting is the most common silvicultural approach), some of the above material has been verified in the northeast. Bormann et al (1969), in a study of a small watershed in the White Mountains of New Hampshire, noted that 1.4% of the watershed was included in the actual stream channel and that debris pools occurred every 1-3 meters. They speculated that these pools served to slow the movement of suspended material from the watershed and reduce the erodibility of the system. Bormann et al. (1974) note that in mature forests the export of particulate material is derived from material stored in the stream bed. However, they note that most of this material moves very little, and approximately 90% decomposes slowly in place.

The above discussion highlights the need for careful consideration of lands adjacent to tributaries. In developing management plans for these areas, consideration should be given to the need for stability of the cover type and forest structure, given the potential occurrence of major disturbances. However, the benefits of the slow addition of natural wood-fall to these areas, and the erosion impediments and the stream pools created by this material, should also be considered. In assessing the management of stream buffers, Stone (1973) recommends careful thinning of buffer strips as often preferable to complete non-disturbance, as such thinning will limit the amount of debris falling directly into streams. Vellidis (1994) found that forested riparian strips next to agricultural lands took up and removed nutrients in soil and vegetation, preventing agricultural outputs from reaching streams. The author recommends that these forested strips be harvested periodically, if they are to serve as an effective nutrient buffer, to ensure a net active uptake of nutrients.

10.2 Even-Aged Silviculture

10.2.1 Water Yields

Beginning at Wagon Wheel Gap in Colorado in 1911, experiments relating forest removals to water yield increases have been conducted at a number of small watershed locations throughout the U.S. Since 1940, three U.S. Forest Service Experimental Forests have supplied the bulk of the data for eastern U.S. applications. These forests are Hubbard Brook, NH; Fernow, WV; and Coweeta, NC. Experiments have included a wide variety of approaches ranging from clearing of small watersheds to patch, partial, and riparian cuts. Most experiments are paired watershed studies, where two small, adjacent or similar watersheds are studied; one watershed is treated silviculturally while the other is left uncut, as a control.

Experimental findings show several general trends. However, variation due to site conditions such as slope, aspect, soils, geology, cover type, and additional factors make exact prediction of water yield increases difficult for a given site. Douglas (1983) notes that yield increases can be predicted within 14% of actual values. Federer and Lash (1978) developed a small watershed computer model aimed specifically at predicting water yield increases from forest management of small watersheds in the northeast, using input variables of precipitation, temperature, latitude, slope, aspect, cover type, and soils.

The following general trends emerge from the many watershed experiments that have been reviewed for Division Land Management Plans:

- Water yields increase as the percentage of forest cover removed increases. Complete removal of hardwood cover on small watersheds can result in first-year yield increases of 4-14 area-inches (total average annual streamflow in the Northeast is approximately 20-25 area-inches or about 50% of total precipitation).
- Water yields decrease with reforestation of open watersheds and growth of younger forests. There is a linear relationship between the percentages of watershed reforested and water yield decrease. Yield decreases are significant, in the range of 6-7 area-inches lost through significant forest growth/regrowth.
- Water yield increases are greatest the first year after cutting and decline thereafter, usually returning to pre-cutting levels by the fourth to eighth year. Yields on most clearing experiments returned to pre-cut levels within 10 years.
- Water yield increases are generally larger on north versus south facing slopes, with yields up to two and one half times greater for clearings on north facing slopes. One study also showed that west-facing forests used more water than those on east-facing slopes.
- Differences between cut and uncut watershed yields increase exponentially as annual rainfall increases.
- Water yield increases from cutting occurred primarily during the growing season in the many studies in the northeast. Areas of higher snowfall, deep soils, or conifer cover showed larger dormant season increases.
- Removal of conifer forests will yield more water than hardwood forests. Conifers use more water annually and snow interception and evaporation is greater in conifers.

- Conversion of hardwoods to conifers will result in significant losses in water yields. A 25% yield loss was measured on a North Carolina watershed after conversion of hardwoods to white pines.
- Greatest yields are usually achieved through removal of riparian vegetation or lower elevation watershed vegetation.
- Much of the increased flow generated from cutting is seen as increases during low flow periods.
- Increases in peak flows do occur, but are not believed to cause increased flood risk where cutting is implemented on limited areas, resulting in moderate yield increases overall.
- Watersheds with deep soils generate longer lasting yield increases after cutting, and yields are more balanced between growing and dormant seasons. Watersheds with shallow soils generate yield increases focused within the growing season.
- Certain early successional hardwoods use measurably more water than late successional hardwoods. Changes in water yield due to shifts in species composition may last in excess of a decade.
- Yield increases are lower in deep soils and in areas with a rapid regeneration response.

(Douglass and Swank 1972, 1975; Douglass 1983; Hibbert 1967; Federer and Lash 1978; Hornbeck and Federer 1975; Hornbeck et al., 1993; Lull and Reinhart 1967; Mader et al., 1972; More and Soper 1990; Mrazik et al., 1980; Storey and Reigner 1970; Trimble et al., 1974.)

Douglass (1983) and Storey and Reigner (1970) emphasize the significance of the above findings as a way to help meet present and future water supply needs in the eastern United States. In general, it seems evident that even-aged management techniques, especially using clear cutting in large blocks, will have the most dramatic effect on water yields.

While clear cutting of entire reservoir watersheds is not reasonable given water quality concerns (see next section on water quality), judicious rotation of clear cuts may provide significant flow increases, especially during the growing season when improved yields are most needed by water supply managers. A compelling argument has been made that the major difference between even-aged and uneven-aged silviculture is the extent of edges and edge effects that remain following the cutting (Bradshaw, 1992). Streamflow response to logging is proportional to the relative amount of edge created by the timber removal, so that greater relative edge results in less streamflow response, and large clearcuts, with a relatively low edge to opening ratio, produce the greatest streamflow response (Satterlund and Adams, 1992, p. 281).

Douglas and Swank (1972) summarize the value of forestry for water supply managers:

> We can conclude from the experimental watershed evidence in the Appalachian Highlands that cutting forest vegetation has a favorable impact on the water resource by supplementing the supply of fresh water when consumptive demands are most critical. And, the amount of extra water produced can be predicted with a degree of accuracy that is sufficient for many purposes. Although heavy forest cuttings will usually increase some stormflow characteristics on that portion of the watershed cut over, regulated cutting on upstream forest land will not produce serious flood problems downstream.

10.2.2 Water Quality

In describing the influence of even-aged and uneven-aged management upon water quality, most studies reviewed involved either clear cutting (of whole watersheds or in limited blocks or strips - all of which fall under even-aged management) or partial cutting (where part of or most of the overstory is retained). The shelterwood regeneration system is a form of even-aged management involving removal of the forest overstory in stages, generally within 10-30 years. While the cuttings in this system appear initially as partial cuttings, they ultimately require the removal of all or most of the overstory in order to bring about the desired regeneration.

The impacts of even-aged management systems upon water quality vary with intensity and location of management; intensity, layout and maintenance of road systems; and planning and supervision of logging and woods roads operations (Lull and Reinhart 1967; Kochenderfer and Aubertin 1975; Hornbeck and Federer 1975). The water quality parameters principally affected by these activities are turbidity, nutrient levels, and stream temperature.

10.2.2.1 Turbidity

Turbidity is affected by soil exposed in poorly planned, located, and maintained road systems and log landings (Kochenderfer and Aubertin, 1975). For example, gravel access roads may have an infiltration capacity of 0.5 inches per hour, while forests have capacities up to 50 inches per hour (Patric 1977, 1978). Haphazardly built road systems may utilize 20% of a watershed, while well planned road systems may utilize 10% (Lull and Reinhart 1967). In addition to access and skid roads, the total compacted area of a typical logging area including landings may approach 40% (Lull and Reinhart, 1972). MDC/DWM conducted a study in 1986 of pine thinning on the Wachusett Reservoir watershed completed by Division watershed crewmembers and two private loggers under Division supervision. For this study, the total area impacted by logging - including access roads, skid roads, and landings - ranged from 14.8% (Division crew) to 19.6% (private loggers) (Kyker-Snowman 1989b). Stone (1973) reported soil disturbances covering 15.5% of the logged area for selection cutting, versus 29.4% for clear cutting in eastern Washington. Sediment export was directly proportional to the percentage of a watershed in roads and reducing this percentage was seen as critical for reducing sediment in streams in the Pacific Northwest (Dyrness, 1965).

Hornbeck, et al., (1986) report that increases in soil disturbance means greater erosion. Martin (1988) recommends setting predetermined travel routes for equipment and doing winter logging and using tracked vehicles rather than wheeled vehicles in sensitive areas. Hewlett (1978) recommends avoiding locating roads near perennial and intermittent stream channels in order to eliminate impacts.

A study of erosion on New York City's water supply watersheds highlighted the importance of protecting road and stream banks from the effects of erosion (S.U.N.Y., 1981). This study of the erosion sources at the Schoharie Reservoir estimated that while road banks made up only 0.22% of the watershed, they were the source of 11% of all erosion. Streambanks, which made up only 0.44% of the watershed, were the source of 21% of all erosion.

Gravel access roads generally represent the only areas of exposed soil on forested watersheds. As such, they are the greatest potential non-channel source of sediment (Satterlund and Adams, 1992). Proper maintenance is required to eliminate the potential adverse impacts on water quality. The rainfall erosion index (EI) of a storm is its total kinetic energy times its maximum 30 minute intensity

(Wischmeier and Smith, 1965). For the New England region, the average annual EI value is between 100 and 150. These values vary with soil type, but with gravel roads they are fairly consistent.

The greatest force exerted by water is generally the impact of raindrops when they hit. On forested watersheds this impact is mitigated by litter cover (Satterlund and Adams, 1992). On non vegetated road surfaces rainfall can detach and move soil particles. On level soils there is no net soil movement, and thus no net erosion, unless overland flow occurs (Satterlund and Adams, 1992). Overland flow from roads starts as rill erosion (small riverlets) that moves down slope. As these coalesce they form channels that increase in volume and erosive force. Erosive force of moving water is directly proportional to its mass (volume) and velocity (Brooks et al., 1992). The velocity and volume of water is affected by increases in slope and length of slope.

Measures that reduce the volume of water carried and the velocity at which it moves will reduce its erosive force. The prompt removal of water from road surfaces reduces velocity and volume by reducing the duration of contact with exposed surfaces and by shortening slope distance. These are accomplished by maintaining a proper crown of the road surface, by ditching the road edges and by maintaining release ditches to carry water away from the road. Crowned roads give the greatest control over water. Grading reshapes the road surface removing ruts and holes providing a smooth crown so water moves laterally into side ditches off the exposed surface.

Slope and the type of road material also affect the potential erosion risk for access roads (Satterlund and Adams, 1992). As slopes increase water velocity increases as does the erosive force of a given volume of water. Road materials vary in their ability to resist the force of detachment and movement. Particle size and compactability determine a material's resistance to erosion. As particle size increases the force required to dislodge and to move them increases. The attraction between particles acts to increase the force required to detach particles, decreasing the risk of erosion. Vegetation increases resistance to the erosive force of moving water by helping to bind soil particles into conglomerates and by decreasing the velocity of water (Brooks, et al., 1992). Construction of new access roads carries the greatest risk of erosion. Stone (1973) notes that some turbidity is inevitable with construction and initial use of new roads, but that almost all continuing damage from roads is avoidable by using recommended woods roads maintenance techniques.

A comparison study of graveled and ungraveled forest access roads in West Virginia showed that the application of even 3 inches of gravel reduced sediment losses eight-fold, even though the gravel road carried two times the traffic of the ungraveled road (Kochenderfer and Helvey 1974).

Lynch et al. (1975) traced increased turbidity on watersheds in Pennsylvania to scarified log landing areas. However, Kochenderfer and Aubertin (1975) report that:

> Bare soil exposed by road building, and to a much lesser extent by log landings, has long been recognized as the major source of stream sediment associated with logging operations.

Turbidity in a West Virginia watershed that was clearcut was traced to both road erosion and channel scour from heavier overland flow (Patric 1976). Channel scour is an impact that is unique to large-scale disturbances where peak flows may increase.

Mechanical compaction of soil reduces soil infiltration and reduces tree seedling survival (Martin 1988). Erosion problems result when mineral soil is exposed to rain, especially on areas with long, steep slopes. However, even compacted, exposed soils have high infiltration capacities. The most significant erosion occurs when soil is bared to the "B" horizon, beneath the organic and leached horizons (Patric 1977).

Division staff measured soil bulk density (a parameter which shows soil compaction) on transects through a pine thinning at Wachusett Reservoir with three types of conventional logging equipment. Average soil bulk densities did not change significantly when measured before and after logging done by the Division's crew with a conventional small skidder and a forwarder. Average bulk density before logging was 6.18 grams/cubic centimeter (gms/cm) and 6.21 after logging; 13 gms/cm is considered the level where root penetration is inhibited. Stone (1973) reported that soil compaction varies enormously with soil type, moisture content, frequency of traffic, and type of "packing" impact. He concluded that the key to avoiding erosion from logging is to ensure that protection steps will handle extreme rain events on the most sensitive sites. The careful planning of skid roads is essential.

Cuttings where soils are not disturbed by roads or skidding do not discernibly increase turbidity (Kochenderfer and Aubertin, 1975; Dyrness 1965; Bormann et al., 1974). In Connecticut, 80 logging locations were checked for compaction, erosion, and stream sedimentation. All such problems were found to be related to the transportation aspects of logging (O'Haryre 1980, as cited in More and Soper 1990). Other studies trace turbidity to erosion from heavily used logging roads, particularly after heavy rainstorms and from increased streamflow that caused channel erosion (Patric 1976; Pierce, et al., 1970 as cited in More and Soper, 1990).

Turbidity measurements were compared on watersheds in the Fernow Experimental Forest, West Virginia; treatments included a commercial clearcut, a silvicultural clearcut, and one watershed with no cutting. Turbidity (in Jackson Turbidity Units – JTU, a precursor to the current Nephelometric Turbidity Units - NTU) during logging was 490, 6, and 2 units respectively. One year after cutting, turbidity was 38, 5, and 2 units respectively (Kochenderfer and Aubertin, 1975). Douglass and Swank (1975) concluded that well-planned, well-maintained road systems do not damage water resources. In a comparison of logging with planned and unplanned skid trails, the planned logging had turbidity of 25 JTU while the unplanned logging had 56,000 JTU (Reinhart and Eschner, 1962, as cited in Brown 1976). A comparison of regulated and unregulated logging in 1947-48 found that unregulated logging increased turbidity 10-20 times background levels while regulated logging increased turbidity only slightly (Douglass and Swank, 1975).

In a study at Hubbard Brook, New Hampshire, a watershed was logged with a strip cut even-aged method. In the two years during and after logging, 6 of 147 streamwater samples exceeded 10 turbidity units (Hornbeck and Federer, 1975). A study of different stream crossing techniques on Division properties in the Ware River watershed found that temporary bridge crossings caused less impact than ford crossings or crossing on poles. Increases in turbidity caused by temporary bridge crossings were not measurable beyond 100 feet downstream from the bridge (Thompson and Kyker-Snowman, 1989).

Clearing of riparian areas has been associated with increased turbidity (Corbett and Spencer, 1975). Lynch, et al. (1975) compared middle slope clear cuts with lower slope clear cuts and found turbidities of 4 part per million (ppm) on middle slope cutting, 196 ppm on lower slopes, and 2 ppm on an uncut control watershed.

While useful predictive models exist to estimate soil loss from agricultural practices, few soil loss predictive models exist for silvicultural operations. Burns and Hewlett (1983) developed a model that evaluated clearcut, disking, and planting operations in the southeastern U.S. This model is based on the percentage of bare soil after logging practices and the location of bare soil areas with regard to perennial stream channels. The authors recommend keeping any exposed soil areas away from wet and dry stream channels, in order to minimize erosion. Currier, et al. (1979) developed a procedure for analyzing water quality impacts from forest management. Larson, et al. (1979) began assembling existing data into a system of computer models. Li, et al. (1979) developed a sediment yield model based on the Universal Soil Loss Equation and tested in Colorado.

10.2.2.2 Nutrients

Logging impacts on nutrient levels can vary by the amount of cover removed, type of cover removed, watershed slope, location within the watershed (lower areas cause faster nutrient input, but higher areas can cause greater nutrient loss), and the timing of the regeneration response. Soil type and depth also control impacts (e.g., deep, poorly-drained, fine-textured soils tend to bind free nutrients before they reach streams) (Bormann, et al., 1968; Brown 1976; Carlton 1990; Martin and Pierce, 1980; Martin et al., 1984). While turbidity increases are caused by soil disturbance, increases in nutrient levels can result solely from cover removal. For example, at Hubbard Brook, New Hampshire, when all trees on a catchment were cut and left on the ground and herbicides applied to prevent regrowth, stream concentrations of several ions increased significantly (Douglass and Swank 1972). In this study, nitrates increased more than forty times background amounts, and exceeded modern drinking water standards (Bormann et al., 1968). Cuttings associated with significant nutrient increases typically involve clearing of large percentages of watersheds. However, even clearing of entire watersheds at Fernow Experimental Forest, WV and Pennsylvania State Experimental Watersheds did not appreciably increase nitrates (Kochenderfer and Aubertin 1975; Lynch et al., 1975), so site conditions are critical to comparisions.

Nutrient increases from cleared areas are derived both from the increases of nutrients released as the decomposition process increases in sunlight and by the reduction in uptake due to the loss of plant cover (Vitousek 1985). At Hubbard Brook, New Hampshire, strip clear-cutting of one third of a watershed caused nitrate increases of nearly two times an undisturbed watershed and one third that caused by a watershed that was completely clear-cut (Hornbeck, et al., 1975). The coarse-textured soils of New England that have lower nutrient-holding ability may be more susceptible to nutrient losses, particularly in areas without plant cover (Hornbeck and Federer, 1975). Soils that are shallow to bedrock, thin unincorporated humus on infertile soil, and coarse skeletal soil on steep slopes are particularly susceptible to nutrient loss (Williams and Mace, 1974). In areas where soils may be sensitive to nutrient loss, limiting cutting to light partial cuts may be necessary to prevent nutrient loss (Brown 1976).

Aber, et al. (1978) modeled changes in forest floor biomass and nitrogen cycling using various regimes of clear-cutting. A projected rotation that clear-cuts a forest each 30 years versus one on a 90 year cycle accumulates less forest floor biomass and may release more nitrogen to streams. Williams and Mace (1974) state that, in general, the more drastic the manipulation of the forest, the larger the corresponding release of nutrients, with minor manipulations causing little or no nutrient release. In their study of jack pine clear-cutting in Minnesota, summer logging involving whole tree removal was found to cause significantly more nutrient leaching than winter logging with only stem removal.

10.2.2.3 Temperature

Stream temperature is important in protecting aquatic life and because of its impact on dissolved oxygen and nutrients (Brown 1976). Stream temperatures vary depending on the presence of forested buffer strips adjacent to stream channels (Hornbeck, et al., 1986). Douglass and Swank (1975) concluded, “Stream temperatures are not increased by forest cuttings if a buffer strip is retained to shade the stream.”

Kochenderfer and Aubertin (1975) found that clear-cuts on upper watershed areas did not increase stream temperature, as few stream channels occur in these areas. In lower watershed cuttings where trees were left adjacent to the stream channel, cuttings had no influence on stream temperature.

10.2.2.4 Summary

Studies indicate that erodibility of a watershed impacted by either natural disturbances or logging will remain low "as long as the disturbance does not involve severe and widespread disruption of the forest floor" (Bormann, et al., 1974). The relevant components of logging operations are skidding, log landing, and access road construction, where mineral soil may be exposed.

While increases in streamwater nutrients vary by type of cutting and watershed characteristics, the two key aspects of cutting that influence nutrient release are the location and extent of clearing and the response of forest regeneration. Even where openings are revegetated within four years by rapidly growing, early successional species, nutrient losses can still occur (Bormann, et al., 1974).

Studies have demonstrated the methods that will hold water temperature and turbidity increases within tolerable limits (Swank 1972). Patric (1978) states there is overwhelming evidence that neither the productivity of soils nor the quality of water is substantially lessened during or after responsibly managed harvests. Stone et al. (1979) report that if proper precautions are taken, water quality impacts from logging are essentially non-existent. Regarding timber harvesting, Stone (1973) concludes that "adverse impacts can be greatly reduced or entirely avoided by skilled planning and sufficient care."

10.3 Uneven-Aged Silviculture

10.3.1.1 Water Yields

While most of the trends summarized in the even-aged management water yields section above also hold true for uneven-aged management, the effects upon water yield vary. For example, uneven-aged management on north-facing slopes, removing conifers and involving significant percentages of basal area, will probably result in higher water yields than less intensive cuts removing hardwoods on south-facing slopes. However, either approach to uneven-aged management will likely result in smaller water yields than a comparable even-aged management approach. This is due to less dramatic changes in soil moisture and evapotranspiration caused by the smaller openings used in uneven-aged management. Adjacent vegetation and advance regeneration more quickly fill these smaller gaps. In addition, the higher ratio of edge to opening in selection system silviculture results in higher utilization of the additional soil moisture created by cutting. Hunt and Mader (1970) found that when two white pine forest plots at Quabbin Reservoir were thinned by 30% and 80%, soil moisture increased slightly to moderately and growth increased by 70% and 230% respectively. Hornbeck, et al. (1993) reported that when 24% of a basin was cut in one clearing it yielded twice the water of a similar basin where 33% of the forest was removed in scattered openings.

Douglass (1983) found that "partial cuttings were not as efficient for augmenting water yield as were complete cuttings." Storey and Reigner (1970) note:

> There are several ways we can manipulate vegetation to effect water savings. The obvious one is by heavy cutting of trees, thereby removing rainfall intercepting surfaces and removing the transpiring agent. According to considerable evidence our people have collected,

single tree selection cutting saves little or no water. The cutover area need not be large; cutting in blocks or strips or even group selection of trees to be removed will save water.

While it is clear that silvicultural systems employing partial cuttings yield less water than complete cuttings, partial cutting studies do show increased yields (Mrazik et al., 1980). For example, of the ten selection cut or thinning watershed experiments in the U.S. listed by More and Soper (1990), eight resulted in significant yields. The average annual yields for each of the first five years after cutting ranged from 0.4 to 2.3 area-inches. On average, selection/thinning resulted in a yield of 1 area-inch per year for the first five years after cutting. Hibbert (1967) reported results of seven selective cuttings in North Carolina and West Virginia in which all watersheds except one had a southerly exposure. The average annual yield for years measured after cutting was 1.13 area-inches. The lightest cuttings necessary to produce significant yield increases remove approximately 25% of the forest basal area (Kochenderfer and Aubertin 1975; Trimble, et al., 1974). Douglass and Swank (1972) assembled a model that predicts a first year water yield increase based on reduction in forest basal area. This model predicts that a 30% reduction in basal area will increase yields approximately 2-3 annual area-inches.

In predicting the significance of water yields to be derived from uneven-aged management, specific site characteristics of watersheds must be examined. For example, cuttings on north facing watersheds with deep soils will result in relatively larger yields. Using regression lines from Hibbert (1967), a one-third reduction in forest cover on a north-facing watershed is estimated to yield three times the streamflow of a similar cut on a south-facing watershed.

Yields from uneven-aged management should also be viewed in comparison to even-aged management and natural management. In general, yields from uneven-aged management should fall between those from even-aged management and natural management. Numerous studies have shown that water yield increases for the first year after cutting is roughly proportional to the percentage reduction in basal area of the forest cover (Douglass and Swank, 1972; Hewlett, 1982), although this reduction must exceed 25% to begin to result in a water yield increase. As forest areas regrow without further disturbance, these yields decline. Hibbert (1967) reports on three small watersheds (all less than 2,000 acres) in New York where an average of 47% of the watersheds was planted to conifers. After 25 years, the three watersheds averaged 5.3 area-inches less streamflow than prior to the planting. Another medium sized watershed (over 300,000 acres) that was passively managed for 38 years and on which average basal area doubled, showed a decrease in yield of 7.7 area-inches - equivalent to a 25% reduction.

Some of the largest yield increases resulting from clearcutting of 100% of a watershed were recorded on the Marcell Experimental Forest, Catchment #4, in Minnesota. This treatment involved cutting alone, with no subsequent herbicide treatment to suppress regeneration (as occurred on Hubbard Brook, Fernow, and Leading Ridge watershed experiments). At Marcell, even-aged clearcutting resulted in streamflow increases up to 70% within three years of cutting, and a range from 15-70% during all of the first 10 years following cutting. Other evidence shows potential decreases on unmanaged forests of up to 25%. Uneven-aged management falls in between these two approaches, but averages small yield increases (on the order of approximately 5% for the first few years after cutting). On Division watersheds, the maturing forest cover would probably produce fairly consistent yields under a naturally-managed approach, and small to moderate increases under either an uneven-aged or even-aged approach, depending largely on the proportion of any given watershed that was cut, and the pattern of that cutting.

10.3.1.2 Water Quality

Many of the principles underlying the potential for water quality impacts as a result of logging operations apply equally to even-aged and uneven-aged management. In order to avoid repetition, only the potential water quality impacts unique to uneven-aged systems will be reviewed in this section. As with even-aged management, the impacts upon water quality vary with intensity and location of management; intensity, layout, and maintenance of road systems; and planning and supervision of logging and woods roads operations (Lull and Reinhart 1967; Kochenderfer and Aubertin 1975; Hornbeck and Federer 1975).

Uneven-aged systems remove single trees and small groups of trees. In a temperate-region forest study of gap-size impacts on nitrates, Parsons et al. (1994) measured extractable nitrate in soil plots. Within a lodgepole pine forest in Wyoming, gaps were created by removing 1, 5, 15, or 30 trees. The authors found that, compared with adjacent undisturbed forest, gaps created by removing 1 or 5 trees had no increase in nitrate. The 15-tree gaps had higher nitrate levels, and 30-tree gaps had nitrate levels 2-3 times higher than the 15-tree gaps. This same stand was previously thinned with no increase in nitrates, and clear-cut with soil nitrate increases of 10-40 times those in adjacent undisturbed forest. The authors recommend selective harvesting if nitrogen availability is of concern on a site. Stone (1973) notes:

> Any management practices that reduce vigor of the residual vegetation or delay regrowth and regeneration - such as scarification, excessive herbicide application, or maintenance of excessive deer herds - could increase loss rates [nitrate leaching] above those observed on the harvest clearcuts. On the other hand, greater surface soil shading, as by partial cutting methods, narrow stripcuts, increased cover density on clearcuts, or any means of hastening regrowth, would reduce losses [nitrate leaching] even more.

Satterlund and Adams (1992, p.278-279) discuss the influence of cutting pattern:

> Pattern has a strong influence on the nature and degree of response to any treatment that modifies a watershed, whether it is the killing or removal of vegetation, compaction or exposure of soil, or rehabilitation of disturbed lands. Pattern, along with type and amount of treatment, is one of the few factors subject to a high degree of management control…By definition, responses to modification of source areas are more pronounced than the same modifications of nonsource areas, for source areas are the portion of any watershed that is tightly linked to the stream system. Any treatment effect is readily transmitted to the channel with little delay or buffering. Similarly, concentrated treatments tend to have greater effects than the same amount of treatment dispersed widely over a watershed. There is greater opportunity to buffer many small dispersed treatments than one large one. In addition, small units may show less response per unit area treated than large ones because of edge effects…For example, if 25% of a forest in several different watersheds was removed by different methods ranging from a singe clearcut to smaller, more dispersed patch cuts or group selection or a uniformly dispersed single-tree selection, the water yield response might range from substantial to negligible, respectively.

Trimble, et al. (1974), in comparing management systems, state that water quality is ordinarily maximized on forest land by maintaining an unbroken tree and litter cover. The City of Baltimore's forest management utilizes the selection system because “although this [selection system] is not the most economical system of cutting to use, it leaves sufficient cover to protect the watershed...”(Hartley 1975).

Research has shown clearly that where stream shading is unaffected, stream temperature will not change (Douglass and Swank 1975; Hornbeck et al., 1986; Kochenderfer and Aubertin 1975). With little significant impact upon temperature and nutrient streamwater parameters, the chief potential impact of uneven-aged management systems is turbidity. However, increased turbidity appears to be less of a concern with uneven-aged management, due to the lighter cutting practices and the amount of forest cover. For example, a comparison study of two watersheds at the Fernow Experimental Forest in West

Virginia showed only slight elevations of particulates after three selection cuts during the 1950s and 1960s (cuts included 13%, 8%, and 6% of basal area) as compared to an adjacent undisturbed watershed. In a separate study, Corbett and Spencer (1975) reported no turbidity increases from a thinning operation.

One area of potential concern regarding traditional uneven-aged systems is that cutting cycles are often more frequent, meaning more frequent forest entry and more miles of access roads in use at any given time (Stone et al., 1979). However, the actual impacts will depend upon the uneven-aged method adopted. For example, in uneven-aged forests managed for water supply purposes, trees can be grown on longer rotations and longer cutting cycles. Rhey Solomon, water resource manager for the U.S. Forest Service notes "...the way to keep the water flowing and safeguard the forest is to rotate management throughout the watershed" (American Forest Council 1986).